Self-referencing electro-optic frequency combs

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Different combs for different jobs

Electro-optic modulation combs

Features: Wide mode spacing, tunable, mWs per mode, COTS + scalable fabrication, retrace
Challenges: Low pulse energy, narrow BW, electro-optical noise

Modelocked laser comb

Features: Large pulse energy, wide BW, many examples self-referenced
Challenges: Narrow mode spacing, modelocking, power per line
Self-referencing EOM & Kerr combs

Electro-optic modulation (EOM) comb

CW pump → Intensity mod. → Phase mod. → + → EDFA → Nonlinear media → f-2f

f_{eo} \rightarrow \Delta \phi

CW laser is the center of comb

Kerr microcomb

CW pump → + → EDFA → micro-cavity → f-2f

f-2f detection gives carrier-offset frequency: \( f_0 = \text{CW laser} - 19,340 \times 10 \text{ GHz} \)

microcombs: EPFL, Caltech, OEwaves, JPL, Cornell, NIST, Purdue, Yale, Columbia, FEMTO-ST ...
Outline

Electro-optic modulation (EOM) comb

- Bit on possible applications
- EOM combs, two challenges:
  1. Spectral broadening
  2. Electro-optic noise
- EOM/microcombs in practice
- Future perspective

Kerr microcomb
EOM/Kerr comb applications

Molecular identification / spectroscopy

Geodesy/ranging. Grace-FO mission

Quantum-based systems: Comb is a classical phase reference. Microcombs at quantum interface

Cavity optomechanics

Atoms, ions

Microwave systems: ADMX dark matter
Building an EOM comb line-by-line

- CW laser
- EOM comb
- Super-contin.
- Filter cavity
- 10 GHz clock
- 10 GHz x N
- CW optical frequency
- 192 THz
- N x microwave

Laser

EOM comb

Super-contin.

EOM super-contin.
Self-referencing an EOM comb

![Diagram showing the process of self-referencing an EOM comb.](image)

- **CW pump**
- **Intensity modulator**
- **2x Phase modulator**
- **EDFA**
- **HNLF**
- **Optical filter**
- **Line-line filter**
- **EDFA DD-HNLF**

1st-stage:
- Wavelength (nm)
- Optical power spectral density (dBm/nm)

2nd-stage:
- Wavenumber
- Optical power spectral density (dBm/nm)

**f**
- 10 GHz
- 4 W

**2f**
- 2.5 GHz
- 1 W

**f₀** = CW laser – 19340 x 10 GHz

Laser - 19,340 x 10 GHz (MHz)

Beha arXiv 2015
Supercontinuum at 10’s of GHz

- **J band**
  - Power (dB)
  - Wavelength (µm): 1.10 to 1.40
  - EOM comb: 33 GHz, 4 W

- **K band**
  - Power (dB)
  - Wavelength (µm): 2.00 to 2.40
  - EOM comb: 10 GHz, 4 W

- **Microcomb**
  - Optical power (10 dB/div)
  - Wavelength (nm): 1000 to 2400
  - Microcomb: 16.5 GHz, 5 W

- **EOM comb**
  - Frequency (GHz)
  - f2f photocurrent (dB)
  - Frequency (GHz): 7.49 to 7.53
  - EOM comb: 10 GHz, 4 W
Electro-optic noise

\[ f_0 = \text{CW laser} - 19340 \times 10 \text{ GHz} \]

10 GHz → 192 THz
Putting EOM combs to work

- Menlo fiber comb
- EOM comb

**Sensing:** Observe optical reference drift ~70 mHz/s

\[ f_0 = \text{CW laser} - 19340 \times 10 \text{ GHz} \]

**Synthesis:** Locking the EOM seed laser

\[ \text{CW laser frequency (Hz)} \]

\[ \text{CW laser - setpoint (Hz)} \]

Beha arXiv 2015
What might future systems look like?

Silica resonators at 100+ GHz

Silicon nitride comb

Silica comb

Heterogeneous integration

Thin-film lithium-niobate on silicon
Conclusion

Chip-scale combs are an interesting new direction for experimenters.

• EOM combs are based on mature technology.

• Chip-integrated systems on the horizon.

• Basic physics of microcombs remains interesting. Will be a driver of applications in future.
Thank you!

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EOM comb & microcomb self-referencing
<100 Hz linewidth chip-scale lasers
High rep rate SiN combs